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# Evaluation of FRP-based Strengthening Design Criteria for Concrete Structures

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## Abstract

This paper looks at the influence of various parameters in flexural strengthening design specifications, as prescribed by three major international design guidelines namely, ACI440, TR55 and FIB14. A four-level conservativeness frame-work has been highlighted using which flexural conservativeness flowchart is developed to demonstrate how conservativeness is integrated within strengthening design processes at various levels. Various generalised mathematical relationships for flexural strengthening design are also described. Based on these relationships the evaluation of flexural design criteria and their influence on strengthening design, with particular emphasis on residual conservativeness in the design solutions, are presented. The results show that there is significant variation in residual conservativeness of the resultant design solutions obtained using different strengthening design guidelines. Further, it has been shown how the possibility of debonding or rupture failure of the FRP results into different residual conservativeness. A clear mathematical basis for segregating debonding and rupture failure modes as a remedy is also presented.

## 1. Introduction

Deterioration of existing concrete structures under environmental and mechanical influences is a global issue leading to gradual loss of their performance. Additionally, changes in imposed loading or seismic demand may result in under-performing concrete structures. These situations demand structural strengthening in order to restore the performance of the concrete structures. Externally bonded Fibre Reinforced Polymer (FRP) materials are commonly used for strengthening existing concrete structures across the world for a diverse range of applications. This system offers a variety of advantages including good corrosion resistance, ease of handling, adaptability to various shapes of existing concrete elements and high strength-to-weight ratios. Whilst FRP materials provide an economical and sustainable option against replacement of under-performing concrete structures, its long-term performance is relatively unknown due to its short history of use within the construction industry. Therefore, it is not surprising that the design guidelines for FRP-based strengthening are more conservative than is the case for more conventional materials. In order to arrive at a common, efficient and rational global basis for design, it is important to evaluate the influence of such conservativeness on strengthening design. This paper aims to evaluate the design specifications prescribed by three important international guidelines for FRP-based strengthening of concrete structures, namely ACI440.2R (2008), TR55 (2004) and FIB14 (2001).

The behaviour of FRP for structural purposes has been of interest of the researchers worldwide since late 1980s. With the gain in confidence in their use for structural strengthening applications, researchers started focusing towards framing design guidelines since mid 1990s. Saadatmanesh and Malek (1998) presented preliminary version of flexural strengthening design guidelines. They proposed various design equations considering various

possible failure modes namely, crushing of concrete, rupture of FRP, local shear failure of concrete at plate-end and debonding of FRP. These equations lack experimental justifications and strength reduction factors to ensure necessary conservativeness in the design solutions. Rasheed and Pervaiz (2003) presented closed form equations for flexural strengthening design including the strength reduction factor on ultimate flexural capacity of strengthened section and experimental justification. Most strengthening guidelines prescribe design criteria philosophically inline with the above two studies with a blend of experimental and reliability based studies. However, still in their present form they need significant fine-tuning and updating.

The FRP-based strengthening design guidelines suffer from two major limitations in their present form in general. First, the design guidelines vary significantly between one another resulting in significantly differing design solutions in terms of strength, ductility and residual margin of safety (or conservativeness). This, in addition to the FRP based strengthening design being relatively new, with lack of long term performance data and a reliance on empirical formulations, makes it difficult to introduce it to the mainstream. Secondly, the inability to suggest how this strengthening will influence service life performance makes it difficult for authorities and clients to justify the costs and selection of a particular set of materials. These two points demonstrate the acute necessity to have confidence in the design tools used in FRP based strengthening. By having a performance based design process which covers not only the strengthening design itself, but also the pre and post strengthening phases, these limitations can be overcome.

Therefore, the ultimate aim of the project, of which this work comprises a part of, is to develop an automated expert system for FRP-strengthened concrete structures which allows FRP-based strengthening to be brought into mainstream design. This will allow the high potential of FRP composites to be effectively exploited for resolving issues related to existing concrete infrastructure economically and sustainably. Furthermore, this design process presented in form of an expert system will be a useful design and management tool for strengthening of existing concrete structures.

The project has three major objectives. The first major objective is to critically assess, evaluate and interpret the strengthening design criteria prescribed by ACI440, TR55 and FIB14. The second objective is to develop a holistic strengthening design process based on explicit performance criteria (in the form of limit-states). The term holistic implies that it covers all the three stages of a typical strengthening design process including pre-strengthening, strengthening and post-strengthening stages. The third objective is to present the proposed design process in form of expert system (ES). This paper presents the work carried out to date towards the first of these three major objectives.

## 2. Conservativeness Framework in Structural Strengthening

In order to better interpret the residual conservativeness in the resultant design solutions provided by the three considered guidelines, four distinct levels at which conservativeness is intended to be inherited in the strengthening design specifications have been identified [Kansara *et al.* (2009a) and (2009b)]. These are termed level I, II, III and IV conservativeness. Each of them has a specific purpose and is mutually and philosophically independent of one another. Hence, it is possible for a design guideline to drop one or more level of conservativeness without affecting the design process flow, although the resulting residual conservativeness due to such omissions will vary as an obvious consequence. This paper provides an insight into the residual conservativeness through a novel interpretation based on the four-level conservativeness framework.

Level I conservativeness occurs through the prescription of a multiplying factor ( $k$ ) applied to the statistical standard deviation ( $\sigma_Y$ ) to absorb the difference between statistical

mean ( $\bar{Y}$ ) and lower or upper bound value of a property ( $Y$ ) on a probabilistic basis for arriving at the characteristic value of that material property ( $Y_{ck}$ ) [see eq. (1)]. Level II conservativeness is inherited through applying a partial factor of safety ( $\gamma$ ) to  $Y_{ck}$  to arrive at the design value of a property ( $Y_d$ ) [see eq. (2)]. Note that level I and II conservativeness are applied at the material property level. All the three design guidelines provide different approaches to the application of level II conservativeness. Level III and IV conservativeness occur through strength reduction factors, ( $\psi$ ) and ( $\phi$ ) respectively, applied to the flexural strength contribution of the FRP component ( $R_f$ ) and the nominal flexural capacity of the strengthened RC element ( $R_n$ ) respectively. Applications of factors  $\psi$  and  $\phi$  lead to a nominal flexural capacity ( $R_{fn}$ ) and design capacity of a strengthened RC element ( $R_d$ ) respectively [see eqs. (3), (4)]. Level III conservativeness is meant to compensate for various secondary discrepancies, such as shear deformation in the adhesive layer, while level IV conservativeness is to adjust probability of failure of the resulting design solutions.

$$\text{Level I Conservativeness:} \quad Y_{ck} = \bar{Y} - k \sigma_Y \quad (1)$$

$$\text{Level II Conservativeness:} \quad Y_d = Y_{ck} / \gamma \quad (2)$$

$$\text{Level III Conservativeness:} \quad R_{fn} = \psi R_f \quad (3)$$

$$\text{Level IV Conservativeness:} \quad R_d = \phi R_n \quad (4)$$

It is noted that the numerical value of the factor  $k$  (representing level I conservativeness) is most stringent for ACI440 ( $k = 3$ ) followed by TR55 ( $k = 2$ ) and FIB14 ( $k = 1.64$ ). The most stringent numerical values of  $\gamma$  (presenting level II conservativeness) on rupture strain of FRP materials are prescribed by TR55 ( $\gamma = 1.31$  to  $2.93$ ) followed by ACI440 ( $\gamma = 1.05$  to  $2.00$ ) and FIB14 ( $\gamma = 1.2$  to  $1.5$ ). The factor  $\psi$  (representing level III conservativeness) is only suggested by ACI440, while TR55 and FIB14 have not incorporated this level of conservativeness. The factor  $\phi$  (representing level IV conservativeness), for flexural strengthening, is suggested as a strength reduction factor in accordance to the ductility indicated by the strain in the existing internal steel reinforcement ( $\varepsilon_{st}$ ) of the design solution by ACI440, while TR55 and FIB14 limit the capacity of the design solutions when ductility is less than a particular value. A detailed description of all the four levels of conservativeness is given in Kansara *et al.* (2009a).

### 3. Evaluation of Flexural Strengthening

The inheritance of conservativeness in flexural strengthening is relatively straightforward, as can be observed from Fig. 1. It is to be noted, however, that due to the presence of an additional structural component in the form of externally bonded FRP reinforcement with the possibility of it debonding from the concrete substrate, the possible types of failure modes are significantly increased compared to those of an unstrengthened RC section. Kansara *et al.* (2009a) have presented a detailed classification of the possible failure modes for FRP strengthened RC sections in flexure and have highlighted that there exists an incompatibility between the failure modes of unstrengthened and strengthened RC sections with the latter having, in addition to one over-reinforced and one balanced failure mode, three (equivalent) under-reinforced failure modes. In contrast an unstrengthened RC section has only one possible under-reinforced failure mode. Kansara *et al.* (2009a) have also proposed new definitions of classical failure modes to overcome this incompatibility resulting in three possible governing failure modes, namely FRP failure, concrete crushing and balanced failure modes which are analogous to under-reinforced, over-reinforced and balanced failure modes.

The proposed failure modes are explicitly based on the strain in the internal tension steel ( $\varepsilon_{st}$ ) termed as the critical steel strain ( $\varepsilon_{st-crit}$ ) for the balanced failure mode. The strain state in the steel reinforcement for the other two failure modes namely, FRP failure governing and concrete crushing governing failure modes, can be depicted as ( $\varepsilon_{st} > \varepsilon_{st-crit}$ ) and ( $\varepsilon_{st} < \varepsilon_{st-crit}$ ) respectively. It is to be noted that unlike conventional RC beam designs, failure modes with concrete crushing represented by strain-state ( $\varepsilon_{st} < \varepsilon_{st-crit}$ ) are permitted in case of FRP-strengthened RC beam designs. The relatively less ductility of these failure modes are compensated through level IV conservativeness as mentioned earlier.

In addition to the incompatibility of failure modes as discussed above, Kansara *et al.* (2009b) have highlighted two further major issues pertaining to flexural strengthening. The first is due to the possibility of two failure mechanisms for the FRP component, namely rupture and debonding. Typically the failure mode of the FRP component is captured in terms of strain in the FRP. Thus, there can be two permissible strain values of the FRP, one corresponding to rupture ( $\varepsilon_{fd-rupture}$ ) and one for debonding ( $\varepsilon_{fd-debond}$ ), the minimum of which will be the governing failure strain ( $\varepsilon_{fd}$ ) [see eq. (5)]. It is to be noted that level I and II conservativeness is applied to the rupture strain of the FRP but not to the debonding strain. It has been shown that for the design solutions with failure modes involving debonding of FRP, level I and II conservativeness do not get inherited [Kansara *et al.* (2009a)]. Further, an upper limit of the mean rupture strain of the FRP component ( $\bar{\varepsilon}_f$ ) termed as the critical mean rupture strain ( $\bar{\varepsilon}_{f-crit}$ ) has been derived which can be used to segregate debonding failure mechanisms from that of rupture failure mechanisms [see eqs. (6)-(7)]. If the designer selects FRP material having  $\bar{\varepsilon}_f$  more than  $\bar{\varepsilon}_{f-crit}$ , the resulting failure mode will be governed by debonding of FRP and not by rupture. Indeed, this is typically the case for surface mounted FRP strengthening solutions. In such cases, level I and II conservativeness will not be inherited into the design solutions and thus the high rupture strain potential of the FRP material is not fully utilised.

$$\varepsilon_{fd} = \text{Min}[\varepsilon_{fd-debond}, \varepsilon_{fd-rupture}] \quad (5)$$

$$\bar{\varepsilon}_f > \bar{\varepsilon}_{f-crit} \Rightarrow \varepsilon_{fd-rupture} > \varepsilon_{fd-debond} \Rightarrow \varepsilon_{fd} = \varepsilon_{fd-debond} \quad (6)$$

$$\bar{\varepsilon}_f < \bar{\varepsilon}_{f-crit} \Rightarrow \varepsilon_{fd-rupture} < \varepsilon_{fd-debond} \Rightarrow \varepsilon_{fd} = \varepsilon_{fd-rupture} \quad (7)$$

The second issue is that the design solutions obtained following the different design guidelines result in considerably different residual conservativeness. Fig. 2 presents this observation graphically in terms of a residual conservativeness index (*RCI*). *RCI* is given by eq. (8) where  $\xi$  is ( $M/bd^2$ ) where  $M$  is flexural capacity and  $b$  and  $d$  are width and effective depth of the RC section respectively. The subscripts 1 and 0 indicate the inclusion and omission respectively, of conservativeness levels I to IV when obtaining ( $M/bd^2$ ).

$$RCI = 1 - (\xi_1 / \xi_0) \quad (8)$$

It can be clearly seen from Fig. 2 that, in spite of presenting the most stringent values of the factor  $\gamma$  and a relatively high value of the factor  $k$ , TR55 provides the lowest residual conservativeness in terms of *RCI* amongst the three design guidelines for most of the possible range of design solutions. One of the important reasons behind this is that TR55 (and FIB14 also) does not incorporate level III conservativeness. Furthermore, it is observed experimentally that debonding of FRP component is more likely to occur than rupture, and

hence most design guidelines prescribe relatively very low values of  $\varepsilon_{fd-debond}$ . Due to such stringent debonding criteria, debonding of FRP component is more likely to govern the failure of the FRP component [eq. (5)]. As discussed earlier, conservativeness level I and II, which are applied to FRP rupture, do not get inherited into the design solutions for the failure modes involving FRP debonding.

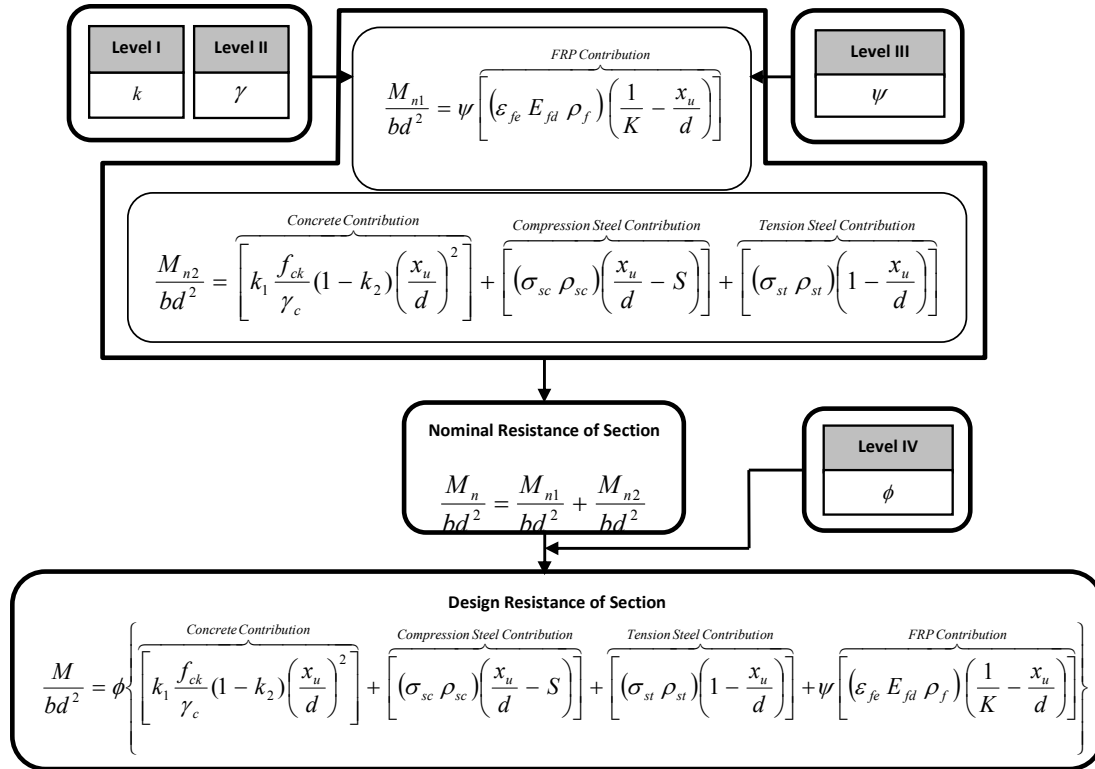


Figure 1: Conservativeness flowchart for flexural strengthening design

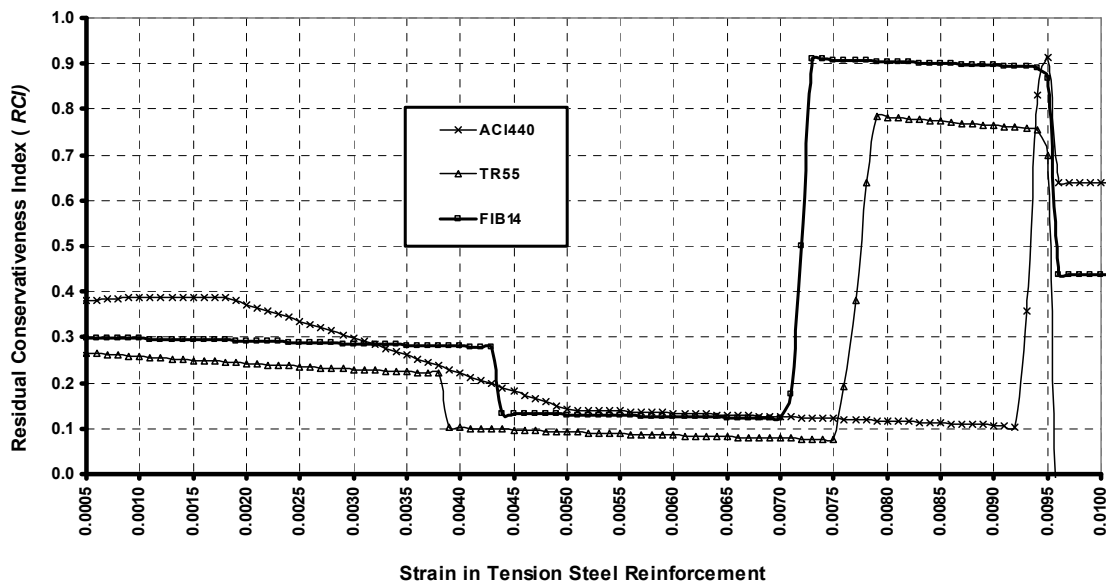


Figure 2: Typical RCI plot for flexural strengthening

## 4. Summary and Conclusions

A four-level conservativeness framework incorporated in FRP strengthening design guidelines has been identified and discussed in this paper. Using this framework, generalised FRP-based flexural strengthening design procedures has been developed. This generalised design procedure demonstrates how conservativeness is integrated into, and feeds through, the entire strengthening design process and serves as useful comprehensive tool for evaluation of strengthening design criteria prescribed by various guidelines. A discussion of the resulting residual conservativeness based on three important international guidelines for the case of flexural strengthening has been presented. The following conclusions can be reached:

1. For the FRP component of the strengthened RC section there are two possible failure mechanisms involving either rupture or debonding of externally bonded FRP. The design guidelines specify partial factors of safety on rupture of the FRP material, while there is no explicit mention of partial factors of safety on debonding failure mechanisms (although they may be implicit within the various limiting conditions described for debonding). Thus, the failure modes involving FRP debonding do not carry the intended conservativeness to the final design solution.
2. There exists an incompatibility between the classical flexural failure modes of un-strengthened RC and FRP-strengthened RC sections. A new definition of classical failure modes is proposed to overcome this inconsistency where equivalent over-reinforced, under-reinforced and balanced sections are developed.
3. The design criteria specified by various strengthening guidelines across the world vary to a significant extent. This results in significantly different conservativeness in the resulting design solutions.
4. Amongst ACI440, TR55 and FIB14, the latter two omit level III conservativeness. Consequently, in spite of proposing relatively high level I and II conservativeness, TR55 consistently results in the lowest residual conservativeness amongst the three design guidelines.

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